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Technical Letter
No. 1110-2-322

15 October 1990

Engineering and Design
RETAINING AND FLOOD WALLS

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Engineering and Design
RETAINING AND FLOOD WALLS

1. Purpose. This engineer technical letter (ETL) provides supplemental material to engineer manual EM 1110-2-2502, "Retaining and Flood Walls."

2. Applicability. This ETL applies to HQUSACE/OCE elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having responsibilities for the design of civil works projects.

3. References.

a. EM 1110-2-2103, "Details of Reinforcement - Hydraulic Structures."

b. EM 1110-2-2502, "Retaining and Floodwalls."

4. Summary.

a. Simplified Pressure Coefficient Method. A simplified method of computing an earth pressure distribution using pressure coefficients which were derived in Appendix H of EM 1110-2-2502 is presented. With this method forces may be computed which are equal to the forces from a wedge analysis.

b. Inclusion of Wall Friction. The general wedge equation as defined in EM 1110-2-2502 (Equation 3-23) is expanded to include the effects of wall friction. The corresponding equations for computing the critical slip plane angle α and pressure coefficients, including the effects of wall friction, are also discussed.

c. Limitation of 2/3 SMF. EM 1110-2-2502 requires the use of a strength mobilization factor (SMF) of 2/3 to compute forces and pressures, using Coulomb's equation (EM 1110-2-2502, Equation 3-11) or the general wedge equation. The value of the SMF equal to 2/3 was developed by comparing the earth pressure coefficient computed using Coulomb's equation for a horizontal backfill with the earth pressure coefficient calculated using Jaky's empirical relationship for predicting at-rest earth pressure coefficients. Using an SMF of 2/3 in Coulomb's equation results in an earth pressure coefficient approximately equal to the value obtained from Jaky's equation. When the slope of the backfill (β) is large compared to the angle of internal friction (ϕ) of the soil (about 60 percent of ϕ), the earth pressures and forces computed using an SMF of 2/3 will exceed the at-rest pressures as computed by the Danish Code equation (EM 1110-2-2502, Equation 3-5). Guidelines are presented to allow the computation of earth pressures for backfills having $\tan \beta / \tan \phi > 0.56$ which agree more closely with the Danish Code equation.

d. Details of Reinforcement. Criteria for steel detailing pertaining to the main flexural reinforcement and the temperature and shrinkage reinforcement for concrete cantilever walls are presented.

5. Simplified Pressure Coefficient Method for Computing Earth Pressures and Forces.

a. Background. In EM 1110-2-2502, pressure coefficients were derived for the calculation of earth pressures. Several coefficients were required to calculate the lateral earth pressures and are defined below:

K = the basic coefficient

K_1 = the coefficient for a sloping ground surface above the water table

K_b = the coefficient to use below the water table

K_v = the coefficient to multiply by V to obtain the horizontal force due to a vertical surcharge

K_c = the coefficient to multiply by $2c$ to obtain the negative pressure due to cohesion

In this ETL, one additional pressure coefficient will be derived called K_H. This coefficient is defined as:

K_H = the coefficient to multiply by $(H_L - H_R)$ to obtain the horizontal force due to external horizontal forces acting on a wedge

A simpler method using only the coefficients K and K_c can be used to compute earth pressures due to the soil geometry. If external forces are present on the wedge, such as a strip surcharge or a horizontal line load, then the pressure coefficients K_v and K_H must be used to determine the lateral force due to these external loads.

b. Applicability. This method can be applied to any soil geometry possessing an angle of internal friction and a cohesion value. The method may be applied to irregular backfills to compute lateral earth pressures in an easy manner. All results from this method compare exactly with values calculated using Coulomb’s or the general wedge equations.

c. Procedure. The procedure to calculate the lateral earth pressure distribution due to the geometry of the backfill is shown in Figure 1. The equation used to compute a horizontal stress at a certain depth is given as

$$p_{hz} = Kp_{vz} - 2K_c c_d \qquad (1)$$

where

p_{hz} = the effective horizontal stress at depth z

p_{vz} = the vertical effective stress at depth z

c_d = the developed cohesion value of the soil, equal to $c \cdot SMF$

z = depth below surface of backfill as shown in Figure 1

This procedure uses a combination of pressure coefficients and backfill geometry to calculate effective horizontal pressures at various depths along the face of the backfill. The vertical pressures shown in Figure 1 are based on the geometry of the backfill. Enclosure 1 demonstrates the relationship between the geometry of the backfill, the vertical effective stresses, and the pressure coefficients.

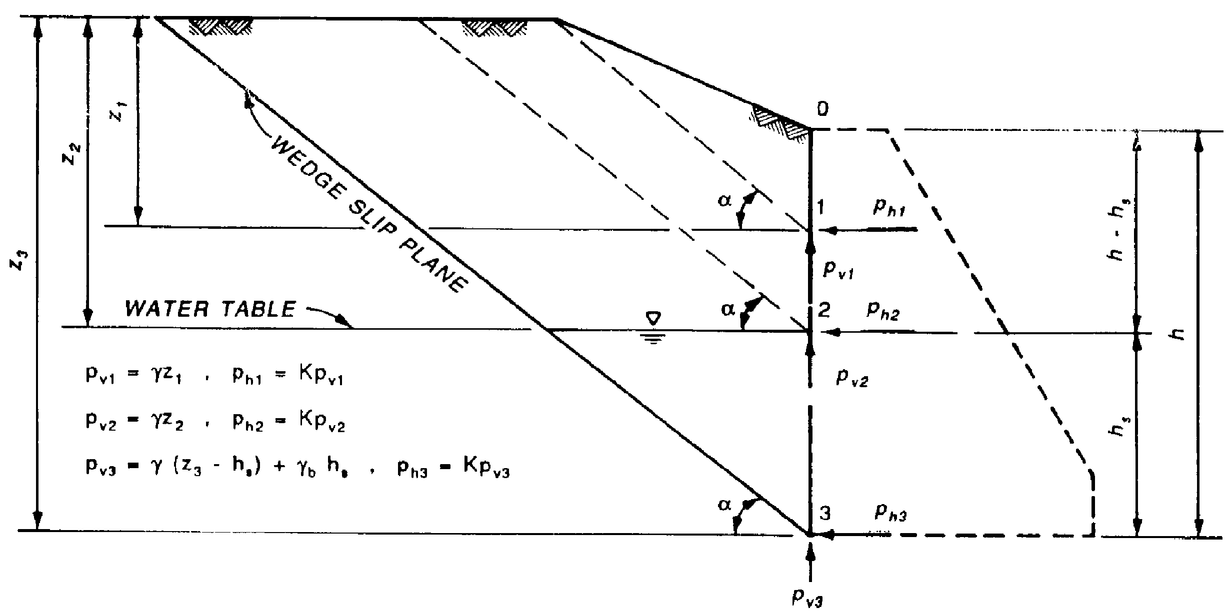


Figure 1. Simplified pressure coefficient method

d. Examples. Examples demonstrating the above method are provided in Enclosure 2.

6. Inclusion of Wall Friction in General Wedge Equation.

a. Background. Friction along the wall-to-soil interface and/or along a soil-to-soil interface is a result of the differential movement of the backfill relative to the movement of the wall and/or differential movement within the backfill. The magnitude and distribution of this shear force are dependent upon several factors, including: the soil type used in the back-fill, the relative movement of the backfill to the movement of the wall, the settlement of the soil relative to the wall resulting from compaction, the distance between the plane on which shear forces are to be computed and the back of the wall, the slope of the ground surface of the backfill, and the presence of any permanent surcharge loadings. EM 1110-2-2502 states in paragraph 3-14 that the friction between the backfill and wall, or on a plane within the backfill, may have a value **between** zero and one-half of the internal friction angle (unfactored) of the backfill material for use in the design. Due to the influence of the previously mentioned factors, which affect the development of this friction force, guidelines for the selection of this friction force used for various categories of walls and backfills will be addressed in subsequent engineering guidance.

b. General Wedge Equation. The derivation for the general wedge equation including wall friction for a backfill with a sloping surface possessing both a ϕ and a c is given in Enclosure 3. The resulting equation for the horizontal effective earth force is defined as:

$$P_{EE} = \frac{(W + V)(\tan\alpha - \tan\phi_d) + (H_L - H_R - P_w)(1 + \tan\alpha \tan\phi_d) + \dfrac{U \tan\phi_d}{\cos\alpha} - \dfrac{c_d L}{\cos\alpha}}{1 + \tan\alpha \tan\phi_d + \tan\delta\,(\tan\alpha - \tan\phi_d)} \qquad (2)$$

where

P_{EE} = horizontal effective earth force contributed by wedge or wedge segment

W = total wedge weight, including water

V = any vertical force applied to wedge

α = angle between slip plane and horizontal

ϕ_d = developed angle of internal friction of the soil, equal to $\tan^{-1}$ (SMF $\tan\phi$)

H_L = any external horizontal force applied to the wedge from the left, acting to the right

H_R = any external horizontal force applied to the wedge from the right, acting to the left

P_w = internal water force acting on the side of the wedge free body (P_w is equal to the net difference of the water force for wedge segments with water on two vertical sides)

U = uplift or buoyant force acting on and normal to the wedge slip plane

c_d = developed cohesion of the soil, equal to $c \cdot SMF$

L = length along the slip plane of the wedge

δ = angle of friction on vertical plane of wedge

The force computed using Equation 2 is the horizontal component of the total effective earth force. The total effective earth force P acts at an angle δ from the horizontal and is given by the following equation

$$P = \frac{P_{EE}}{\cos\,\delta} \tag{3}$$

c. Equations for Determining Critical Slip Plane Angle. Based on Equation 2, the equations for the calculation of the critical slip plane angle may be derived by the procedure shown in Appendix G of EM 1110-2-2502. The resulting equation for the critical slip plane angle is defined as:

$$\alpha_{critical} = \tan^{-1}\left(\frac{c1 + \sqrt{c_1 + 4c_2}}{2}\right) \tag{4}$$

where

$$c_1 = \left\{ 2\tan\phi_d\,(\tan\phi_d + \tan\delta\,) - \frac{4V\tan\beta\,(1 + \tan^2\phi_d)}{\gamma(h^2 - d_c^2)} - \frac{4(H_R - H_L)\tan\beta\,(1 - \tan^2\phi_d)\tan\delta}{\gamma(h^2 - d_c^2)} + \frac{4c_d[\tan\phi_d + \tan\beta + (1 - \tan\phi_d\tan\beta\,)\tan\delta]}{\gamma(h - d_c)} \right\} \div A \tag{5}$$

$$c_2 = \Big\{ \tan \phi_d \,[1 - \tan \phi_d (\tan \beta + \tan \delta)] - \tan \beta$$
$$\frac{2V \tan^2 \beta \,(1 + \tan^2 \phi_d)}{\gamma (h^2 - d_c^2)}$$
$$+ \frac{2(H_R - H_L)\,[\tan^2 \beta\,(1 - \tan^2 \phi_d) \tan \delta]}{\gamma (h^2 - d_c^2)} \qquad (6)$$
$$+ \frac{2c_d[1 - \tan \phi_d + \tan \beta - (\tan \phi_d + \tan \beta) \tan \delta]}{\gamma (h - d_c)} \Big\} \div A$$

Terms used in Equation 5 and 6 are defined as

γ = effective unit weight of the soil (use moist or saturated weight above the water table and buoyant weight below the water table)

d_c = the depth of cracking in a cohesive soil

$$A = \tan \phi_d + \tan \delta - \frac{2V(1 + \tan^2 \phi_d)}{\gamma(h^2 - d_c^2)} - \frac{2(H_R - H_L)(1 + \tan^2 \phi_d) \tan \delta}{\gamma(h^2 - d_c^2)}$$
$$+ \frac{2c_d[1 - \tan \phi_d \tan \beta - (\tan \phi_d + \tan \beta) \tan \delta]}{\gamma(h + d_c)} \qquad (7)$$

The derived equations are valid for a backfill with a planar (flat or inclined) top surface, a vertical strip surcharge V, and a horizontal surcharge equal to $(H_L - H_R)$. The equations for α assume that the backfill is completely above or completely below the water table, but can be used when the water table is anywhere within the backfill with sufficient accuracy for design. The surcharge loads can have any arbitrary shape but must be contained entirely within the driving wedge. By using positive and negative surcharges, Equations 4 through 7 may be used to calculate the critical slip plane angle for irregular-shaped backfills. The effect of water may be taken into account by using the average unit weight of soil for the γ term in Equations 5 through 7. The effect of seepage should be considered in determining the buoyant weight. An example showing the calculation of the buoyant weight is shown in Example 6 of Enclosure 2.

d. Equations for Determining Earth Pressure Coefficients. The following equations for the pressure coefficients were derived from the general wedge equation following the same procedure found in Appendix H of EM 1110-2-2502.

The equation for the effective horizontal earth force written in terms of the derived pressure coefficients is given as:

$$P_{EE} = \frac{K_1 \gamma (h^2 - d_c^2)}{2} + K_V V + K_H (H_L - H_R) - 2K_c c_d (h - d_c) \qquad (8)$$

where

$$K = \frac{1 - \tan \phi_d \cot \alpha}{1 + \tan \phi_d \tan \alpha + \tan \delta \, (\tan \alpha - \tan \phi_d)} \qquad (9)$$

$$K_1 = K \frac{\tan \alpha}{\tan \alpha - \tan \beta} \qquad (10)$$

$$K_V = K \tan \alpha \qquad (11)$$

$$K_H = \frac{1 + \tan \phi_d \tan \alpha}{1 + \tan \phi_d \tan \alpha + \tan \delta \, (\tan \alpha - \tan \phi_d)} \qquad (12)$$

$$K_c = \frac{1}{2 \sin \alpha \cos \alpha \, [1 + \tan \phi_d \tan \alpha + \tan \delta \, (\tan \alpha - \tan \phi_d)]} \cdot \frac{\tan \alpha}{\tan \alpha - \tan \beta} \qquad (13)$$

The effects of the water table may be considered by using a pressure coefficient K_b below the water table. K_b is defined as

$$K_b = K \left[1 + \left(\frac{\tan \alpha}{\tan \alpha - \tan \beta} - 1 \right) \frac{\gamma}{\gamma_b} \right] \qquad (14)$$

The forces and pressures obtained by using the above coefficients are the horizontal components of the total forces and pressures. The total force and pressure acts at an angle δ with respect to the horizontal.

e. Examples. Examples demonstrating the use of the above equations are contained in Enclosure 4.

7. Limitation of Use of 2/3 SMF for Sloping Backfills.

a. Background. EM 1110-2-2502 states in paragraph 3-13b that an SMF of 2/3 should be used with the general wedge equation or Coulomb's equation to predict the at-rest earth forces acting on the driving side of a wall. If an SMF of 1.0 is used with the general wedge equation or Coulomb's equation, then the force computed would be for the active condition. As the SMF is reduced below 1.0, the magnitude of the assigned material strength properties (ϕ and c) decreases, which causes an increase in the lateral earth force computed. The use of an SMF of 2/3 produces a force from the general wedge equation or Coulomb's equation which approximates the force for the at-rest condition. As stated in paragraph 4c, the concept of an SMF of 2/3 was developed by comparing Coulomb's equation for level backfills with Jaky's empirical relationship for predicting at-rest earth pressure coefficients. The actual magnitude of the force computed depends on several factors, which include the soil geometry (e.g. surface slope, irregular), soil properties, and surcharge loading.

b. Applicability. When the slope of the backfill β is large compared with the developed angle of internal friction of the soil ϕ_d, the horizontal earth pressure coefficient computed from the general wedge equation or Coulomb's equation exceeds the value computed using the Danish Code equation. This condition occurs approximately where the ratio $\tan \beta / \tan \phi$ exceeds 0.56. When the ratio $\tan \beta / \tan \phi$ exceeds 0.56, the value of the SMF should increase from 2/3 to cause the coefficient computed from the Danish Code equation and Coulomb's equation to be approximately equal. Also, since the factor of safety is the reciprocal of the SMF, as the SMF increases from 2/3, the factor of safety for the soil wedge will decrease from 1.5. The above discussion pertains to positive values of β. For negative values of β, the SMF should remain at 2/3. For some combinations of β and ϕ, where β is negative, the horizontal earth pressure coefficient computed using the Danish Code equation is less than the coefficient computed using Coulomb's equation for the active condition (SMF = 1.0). The earth pressure coefficient should never be less than the coefficient obtained for the active condition. Therefore, for negative values of β, the more conservative earth pressure coefficient computed using an SMF of 2/3 should be used.

c. Criteria. Tables of values of SMF's to use for various combinations of ϕ's and β's are given in Enclosure 5. EM 1110-2-2502 in paragraph 4-15 describes a procedure for using the soil wedge forces computed by the SMF procedure to determine the factor of safety against sliding. In the table of SMF values, the corresponding factor of safety for the soil wedge will be less than 1.5, as discussed previously. The reciprocal of the SMF for the soil wedge is the limiting value for the factor of safety against sliding when using the single wedge equation procedure as described in EM 1110-2-2502 in paragraph 4-15. For cases where the required factor of safety for sliding is greater than this limiting value, the single wedge procedure cannot be used as a check for sliding stability and a multiple wedge analysis will be required.

d. Examples. An example demonstrating the variance of the horizontal earth pressure coefficient with ϕ and β is shown in Enclosure 6.

8. Details of Reinforcement.

a. Main Flexural Reinforcement. The amount of reinforcement in each part of a reinforced concrete wall should be determined by the currently approved engineering procedure. The minimum clearance and minimum spacing of bars, and the minimum concrete cover requirements should be in accordance with EM 1110-2-2103. Maximum spacing of bars is given in EM 1110-2-2502. More than two rows or layers of reinforcing bars should not be used except where unusual conditions make this procedure necessary, in which case, a special supporting arrangement for holding the bars in their designed locations should be provided in the design and shown on the drawings. Bending and splicing of reinforcement should be in accordance with EM 1110-2-2103.

b. Temperature and Shrinkage Reinforcement. Temperature and shrinkage reinforcement should be in accordance with EM 1110-2-2103. The amount of longitudinal reinforcement for volume changes resulting from shrinkage and temperature changes is intended to control cracking between properly spaced contraction joints in reinforced concrete walls.

c. Typical Steel Details. Typical steel details for a retaining wall and a floodwall are shown in Enclosure 7.

FOR THE COMMANDER:

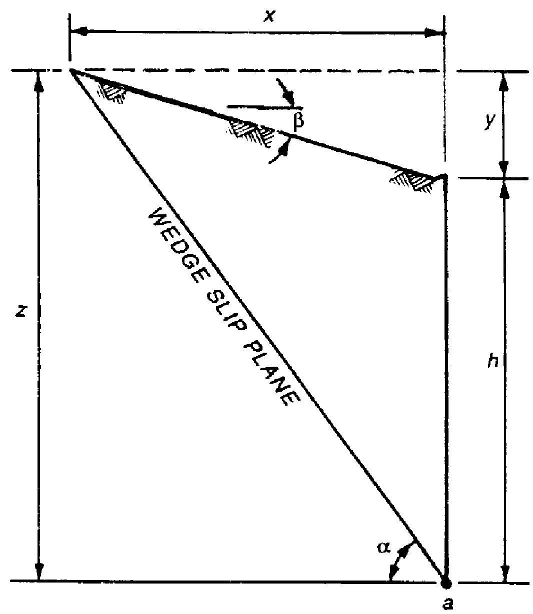
7 Encl

JOHN A. MCPHERSON
Acting Chief, Engineering Division
Directorate of Civil Works

WHY THE SIMPLIFIED PRESSURE COEFFICIENT METHOD WORKS

1. The following discussion will show how the simplified K method is able to predict horizontal earth pressures that equal the pressures computed when using the K's discussed in paragraph 6d of this ETL. Essentially, the basic coefficient K and the coefficient K_1 for a sloping backfill are related by the geometry of the backfill.

2. A basic wedge with a sloping cohesionless backfill as shown below will be examined.



From the figure,

$$\frac{y}{x} = \tan \beta \qquad (1)$$

$$\frac{z}{x} = \tan \alpha \qquad (2)$$

Solving for x in both Equations 1 and 2 and setting the results equal to each other gives Equation 3:

$$\frac{z}{\tan \alpha} = \frac{y}{\tan \beta} \qquad (3)$$

Noting that $z = y + h$ and by substituting in Equation 3 for z and simplifying the following equation results

$$\frac{y - y \tan \beta}{\tan \alpha} = \frac{h \tan \beta}{\tan \alpha} \qquad (4)$$

Substituting $y = x \tan \beta$ into Equation 4 and solving for x yields

$$x = \frac{h}{\tan \alpha - \tan \beta} \qquad (5)$$

From Equation 2, substituting in for x , z equals

$$z = h \left(\frac{\tan \alpha}{\tan \alpha - \tan \beta} \right) \qquad (6)$$

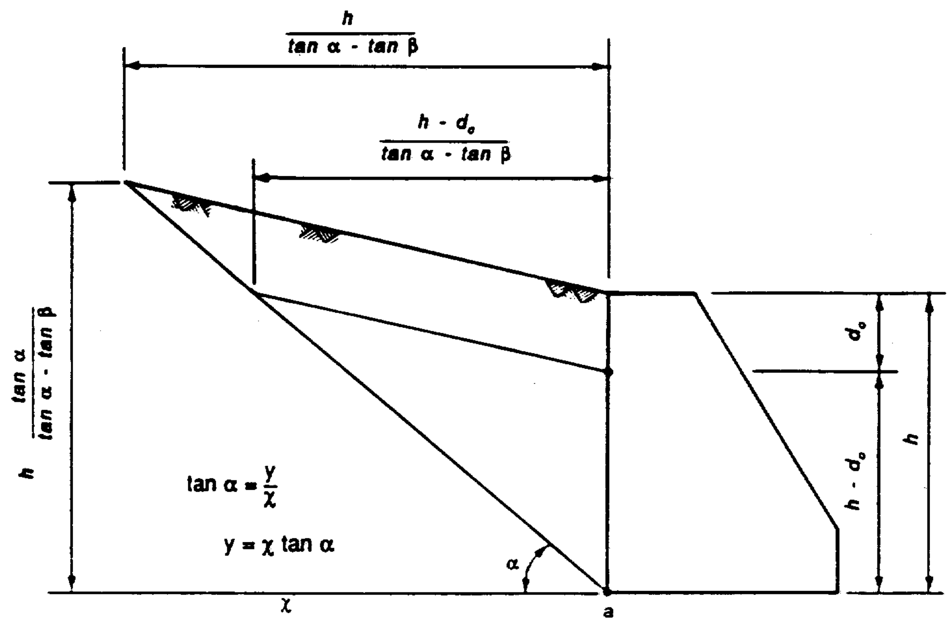
If the pressure at the bottom of the wedge (point a) is calculated using both K and K_1 , the following pressures result

$$P_{ah} = K_1 \gamma h = K \left(\frac{\tan \alpha}{\tan \alpha - \tan \beta} \right) \gamma h \qquad (7)$$

$$P_{ah} = K \gamma z = K \left(\frac{\tan \alpha}{\tan \alpha - \tan \beta} \right) \gamma h \qquad (8)$$

The pressures at point a calculated in Equations 7 and 8 are identical.

3. A basic wedge with a sloping cohesive backfill as shown below will be examined.



If the pressure at the bottom of the wedge (point a) is calculated using both K and K_1 , the following pressures result

$$P_{ah} = K_1\gamma(h - d_c) = K\left(\frac{\tan\alpha}{\tan\alpha - \tan\beta}\right)\gamma(h - d_c) \tag{9}$$

where

$$d_c = \frac{2K_c c_d}{K_1\gamma} \tag{10}$$

Thus

$$P_{ah} = K\left(\frac{\tan\alpha}{\tan\alpha - \tan\beta}\right)\gamma h - 2K_c c_d \tag{11}$$

Using the basic coefficient K and the distance z defined previously

$$P_{ah} = K\gamma z - 2K_c c_d = K\left(\frac{\tan\alpha}{\tan\alpha - \tan\beta}\right)\gamma h - 2K_c c_d \tag{12}$$

The pressures at point a calculated in Equations 11 and 12 are identical.

EXAMPLES OF EARTH PRESSURE COMPUTATIONS USING THE SIMPLIFIED PRESSURE COEFFICIENT METHOD

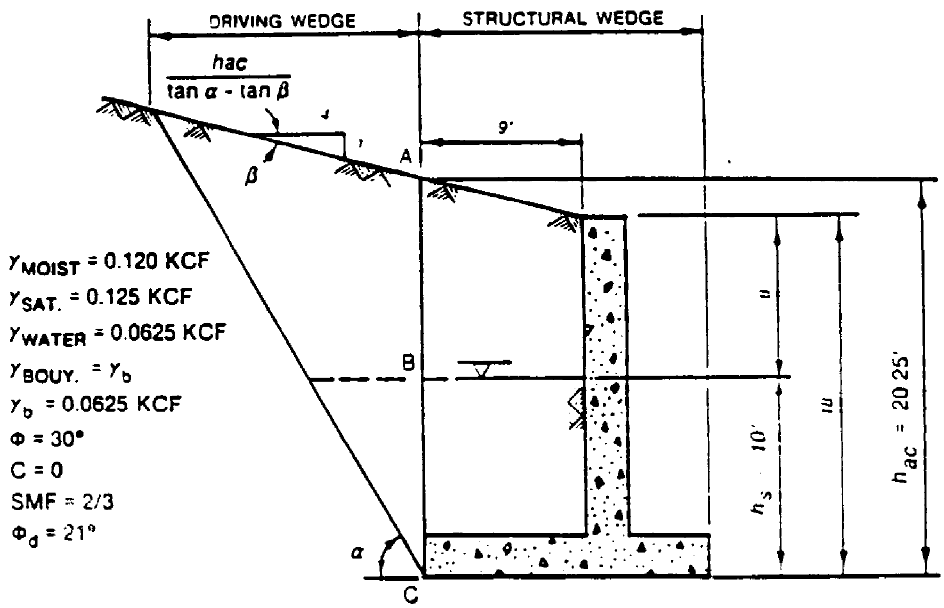
1. The following examples demonstrate the method of computing earth pressures using the simplified pressure coefficient method described in paragraph 5c of this ETL.

2. Examples 1 through 3 of this enclosure are taken from EM 1110-2-2502. The results of the examples are compared against the results obtained using the simplified pressure coefficient method. Example 4 demonstrates additional geometry configurations.

EXAMPLE 1

3. This example is taken from EM 1110-2-2502, Example 3, page M-7. The lateral earth pressures will be computed by the simplified pressure coefficient method and compared to the results from EM 1110-2-2502.

4. The soil geometry and properties are shown in the figure below.



The following values were determined for the problem from EM 1110-2-2502.

$\alpha_{critical}$ = 45.466°

K = 0.44767

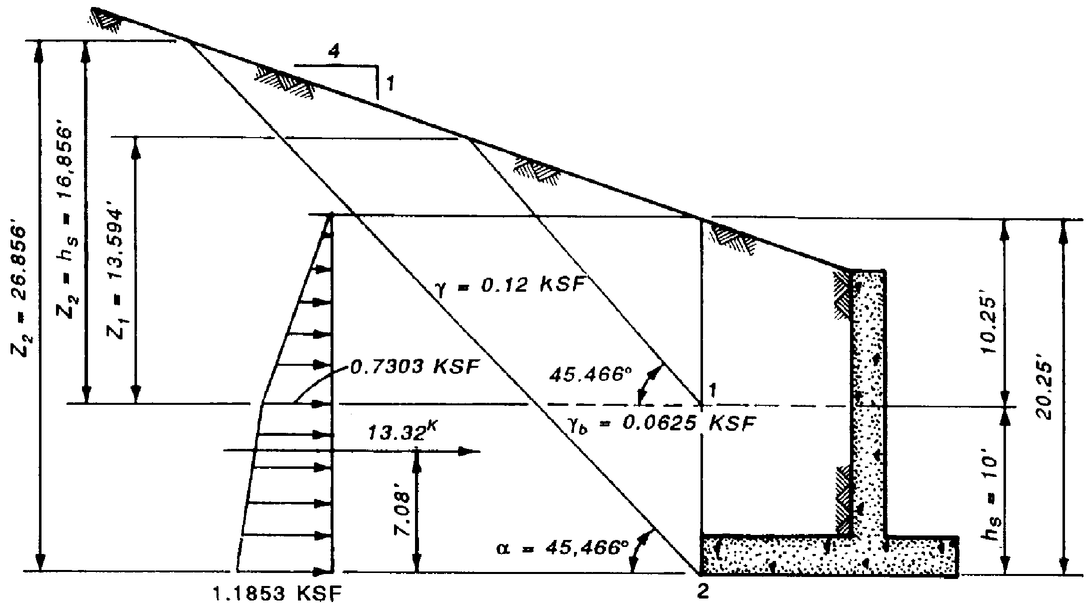
5. The pressures are calculated as follows for the points shown in the figure on the following page

$p_{v1} = \gamma z_1 = 0.12(13.594) = 1.6313$ ksf

$p_{v2} = \gamma(z_2 - h_s) + \gamma_b h_s = 0.12(16.856) + 0.0625(10) = 2.6477$ ksf

$p_{h1} = Kp_{v1} = 0.44767(1.6313) = 0.7303$ ksf

$p_{h2} = Kp_{v2} = 0.44767(2.6477) = 1.1853$ ksf

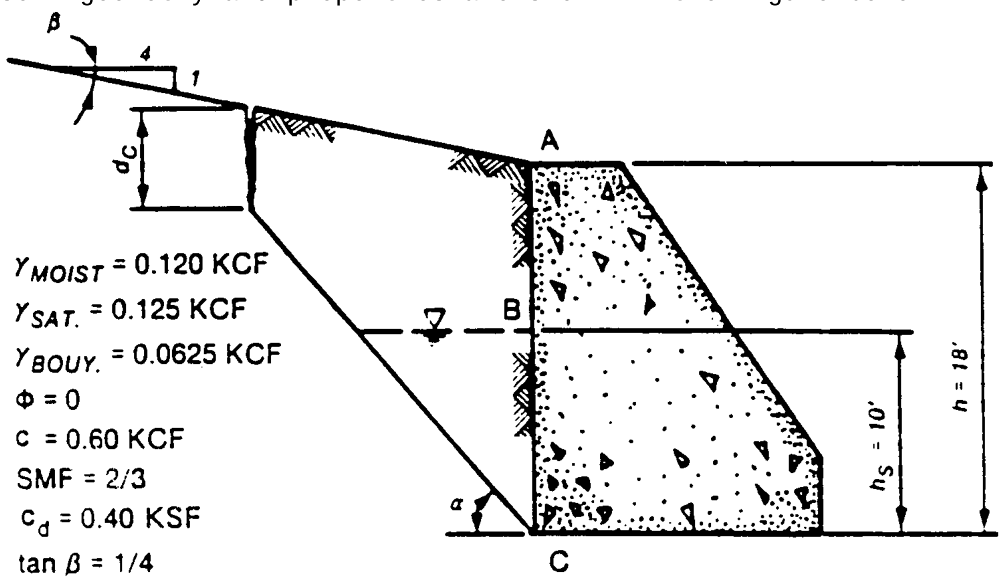


The solution agrees with the solution found in EM 1110-2-2502.

EXAMPLE 2

6. This example is taken from EM 1110-2-2502, example 5, page M-21. The lateral earth pressures will be computed by the simplified pressure coefficient method and compared to the results from EM 1110-2-2502.

7. The soil geometry and properties are shown in the figure below.



The following values were determined for the problem from EM 1110-2-2502

$\alpha_{critical} = 29°$

$d_c = 7.86$ ft

K = 1.00

Using the equation for K_c in Appendix H from EM 1110-2-2502 yields

$$K_c = \frac{1}{2 \sin \alpha \cos \alpha} \cdot \frac{\tan \alpha}{\tan \alpha - \tan ß} = 2.14791$$

8. The pressures for the points shown in the figure below are calculated as follows:

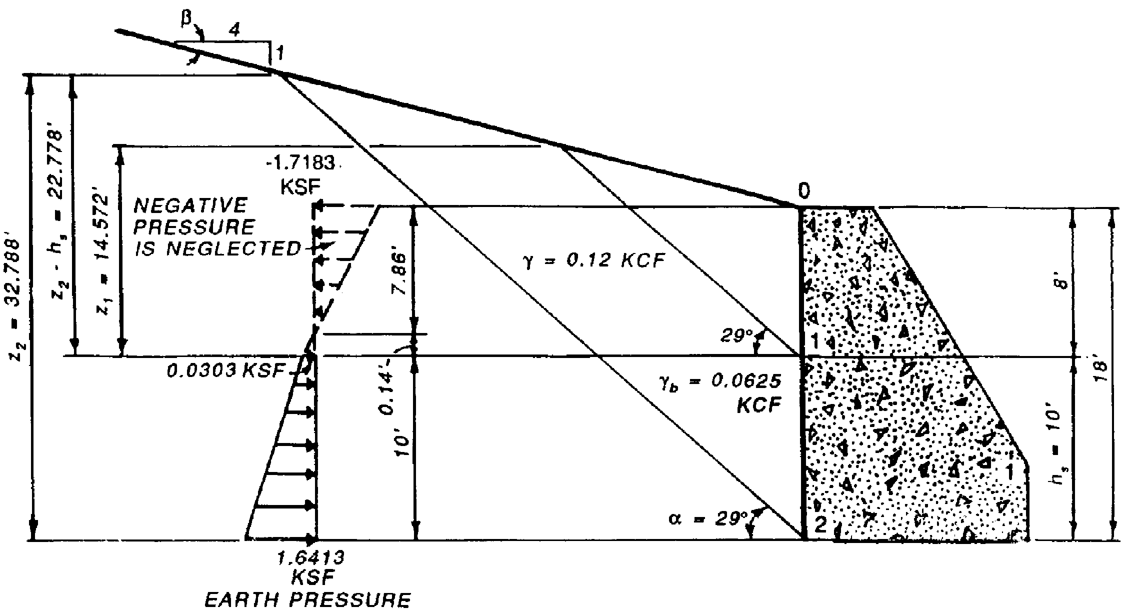
$p_{v1} = \gamma z_1 = 0.12(14.572) = 1.7486$ ksf

$p_{v2} = \gamma(z_2 - h_s) + \gamma_b h_s = 0.12(22.788) + 0.0625(10) = 3.3596$ ksf

$p_{ho} = -2K_c c_d = -2(2.1479)(0.4) = -1.7183$ ksf

$p_{h1} = Kp_{v1} - 2K_c c_d = 1.0(1.7486) - 1.7183 = 0.0303$ ksf

$p_{h2} = Kp_{v2} - 2K_c c_d = 3.33596 - 1.7183 = 1.6413$ ksf

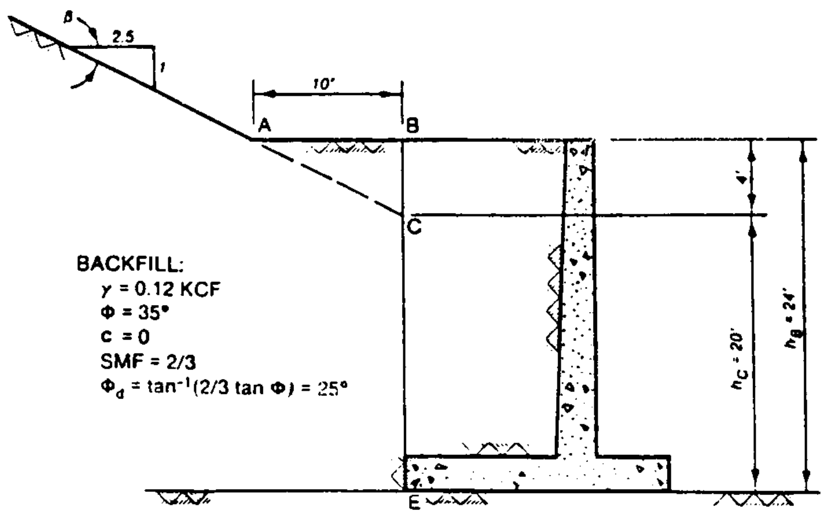


The negative pressures down to depth d_c are neglected. The positive pressures agree with the EM 1110-2-2502 solution.

EXAMPLE 3

9. This example is taken from EM 1110-2-2502, example 9, page M-52. The lateral earth pressures will be computed by the simplified pressure coefficient method and compared to the results from EM 1110-2-2502.

10. The soil geometry and properties are shown in the figure below.



The following values were calculated in EM 1110-2-2502

$\alpha_{critical} = 44.302°$

$K = 0.3589$

11. The pressures for the points shown on the figure on the following page are calculated as follows:

$p_{v1} = \gamma z_1 = 0.12(4.0) = 0.4800$ ksf

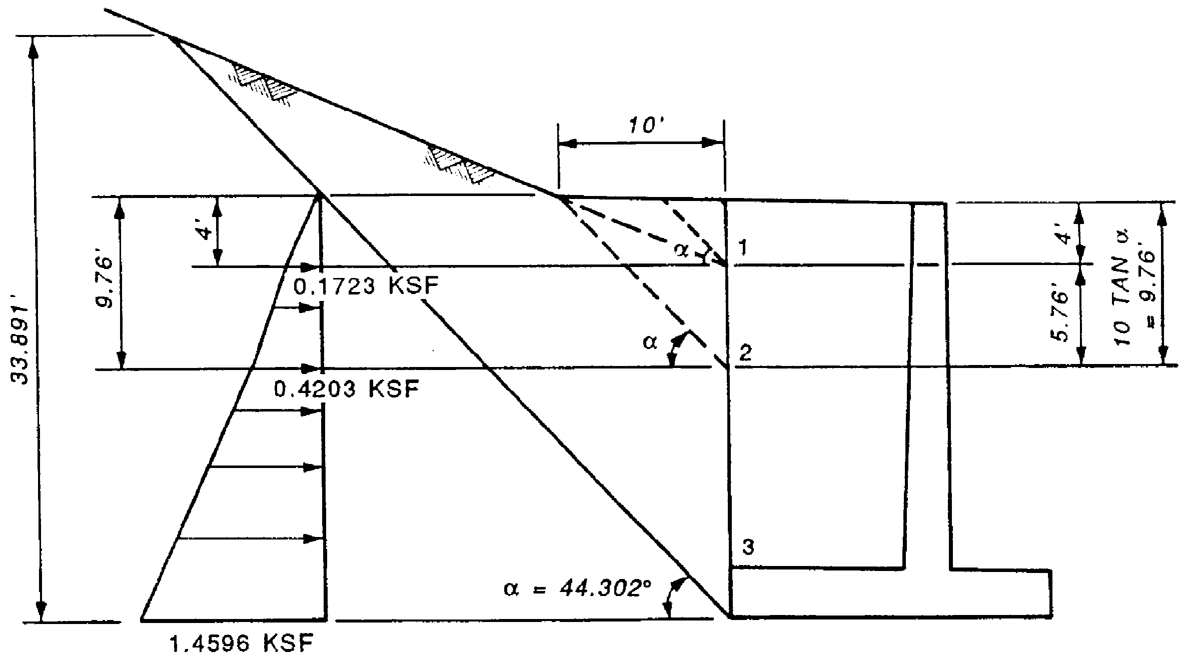
$p_{v2} = \gamma z_2 = 0.12(9.76) = 1.1712$ ksf

$p_{v3} = \gamma z_3 = 0.12(33.891) = 4.0669$ ksf

$p_{h1} = Kp_{v1} = 0.3589(0.4800) = 0.1723$ ksf

$p_{h2} = Kp_{v2} = 0.3589(1.1712) = 0.4203$ ksf

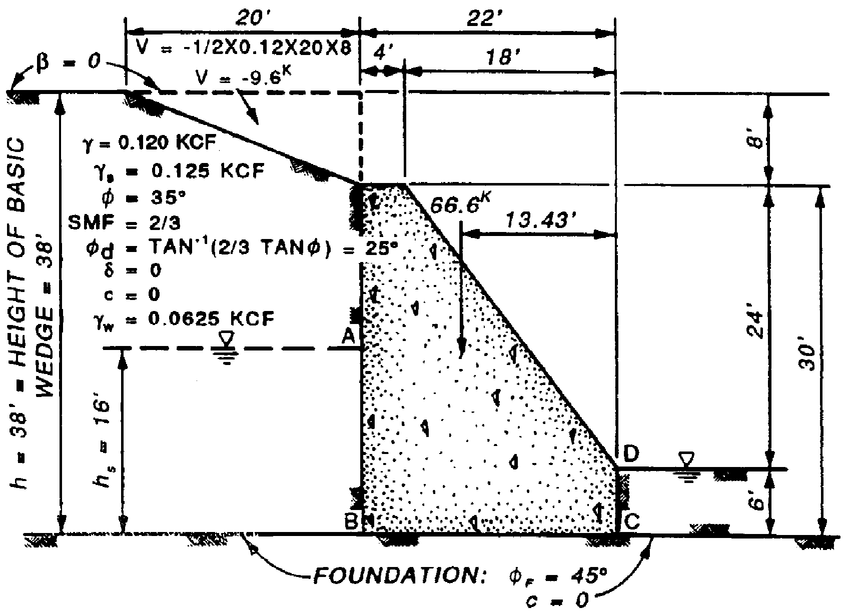
$p_{h3} = Kp_{v3} = 0.3589(4.0669) = 1.4596$ ksf



The pressures calculated agree with the solution found in EM 1110-2-2502.

EXAMPLE 4

12. The lateral earth pressures for the driving side will be computed by the simplified pressure coefficient method for the problem shown in the figure below.



13. The water pressures are calculated using the line of creep method.

Differential head = 16 ft - 6 ft = 10 ft

L_s = Total length of the seepage path = $L_{AB} + L_{BC} + L_{CD}$

= 16 + 22 + 6 = 44 ft

Seepage gradient $i = \frac{10 \text{ ft}}{44 \text{ ft}} = 0.2273$

$u_b = [16 - 0.2273(16)]0.0625 = 0.773$ ksf

$u_c = [16 - 0.2273(16 + 22)]0.0625 = 0.460$ ksf

14. The buoyant unit weights of the soil may now be calculated.

For the left side:

Effective unit weight of water $\gamma_{we} = \gamma_w(1 - i) = 0.0483$ kcf

$\gamma_{bL} = \gamma_s - \gamma_{we} = 0.125 - 0.0483 = 0.0767$ kcf

For the right side:

Effective unit weight of water $\gamma_{we} = \gamma_w(1 + i) = 0.07671$ kcf

$\gamma_{bR} = \gamma_s - \gamma_{we} = 0.125 - 0.0767 = 0.0483$ kcf

15. The critical slip plane angle α and K may now be calculated. To calculate the critical slip plane angle, the average unit weight of the soil in the wedge must be used. This is calculated as

$$\gamma_{avg} = \frac{\gamma h^2 - (\gamma - \gamma_{bL})h_s^2}{h^2}$$

$$= \frac{0.12(38)^2 - (0.12 - 0.0767)(16)^2}{38^2} = 0.1123 \text{ kcf}$$

Also the soil wedge EFG is modeled as a negative surcharge equal to

$$V = -\frac{1}{2}(0.12)(20)(8) = -9.6 \text{ kips}$$

The average unit weight is now used in Equation 3-30 from EM 1110-2-2502

$$A = \tan\phi_d - \frac{2V(1 + \tan^2\phi_d)}{\gamma h^2}$$

$$= \tan 25° - \frac{2(-9.6)(1 + \tan^2 25°)}{0.1123(38)^2}$$

$$= 0.610454$$

From Equations 3-28 and 3-29 from EM 1110-2-2502

$$c_1 = \frac{2 \tan^2 \phi_d}{A}$$

$$= \frac{2 \tan^2 25°}{0.610454}$$

$$= 0.712398$$

$$c_2 = \frac{\tan \phi_d}{A}$$

$$= \frac{\tan 25°}{0.610454}$$

$$= 0.763871$$

The critical slip plane angle α may now be calculated from Equation 3-25 from EM 1110-2-2502.

$$\alpha_{critical} = \tan^{-1}\left(\frac{C_1 + \sqrt{C_1 + 4C_2}}{2}\right) = 52.4313°$$

The basic pressure coefficient K may now be calculated using the following equation from Appendix H of EM 1110-2-2502.

$$K = \frac{1 - \tan \phi_d \cot \alpha}{1 + \tan \phi_d \tan \alpha}$$

$$= \frac{1 - \tan 25° \cot 52.4313°}{1 + \tan 25° \tan 52.4313°}$$

$$= 0.39927$$

16. The earth pressures may now be calculated for the points shown in the figure on the following page.

$$p_{v1} = 0.12(20.222) = 2.4266 \text{ ksf}$$

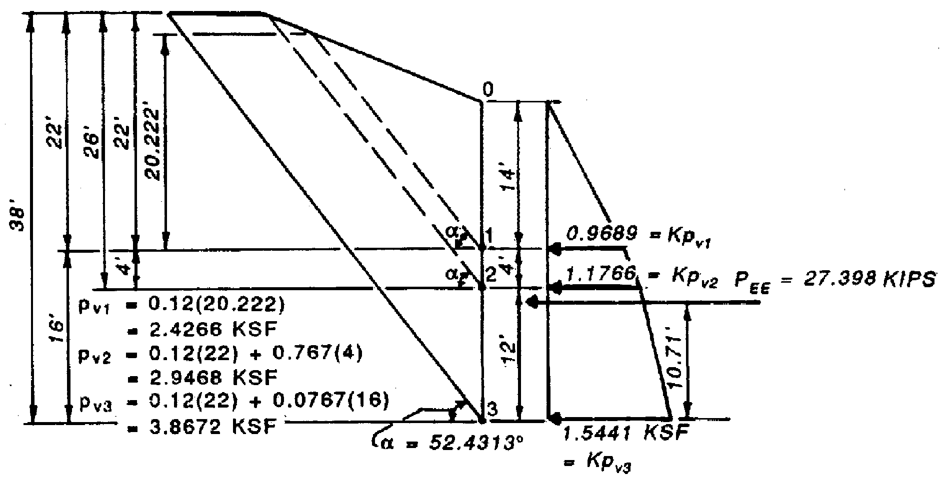
$$p_{v2} = 0.12(22) + 0.0767(4) = 2.9468 \text{ ksf}$$

$$p_{v3} = 0.12(22) + 0.0767(16) = 3.8672 \text{ ksf}$$

$p_{h1} = Kp_{v1} = 0.33927(2.4266) = 0.9689$ ksf

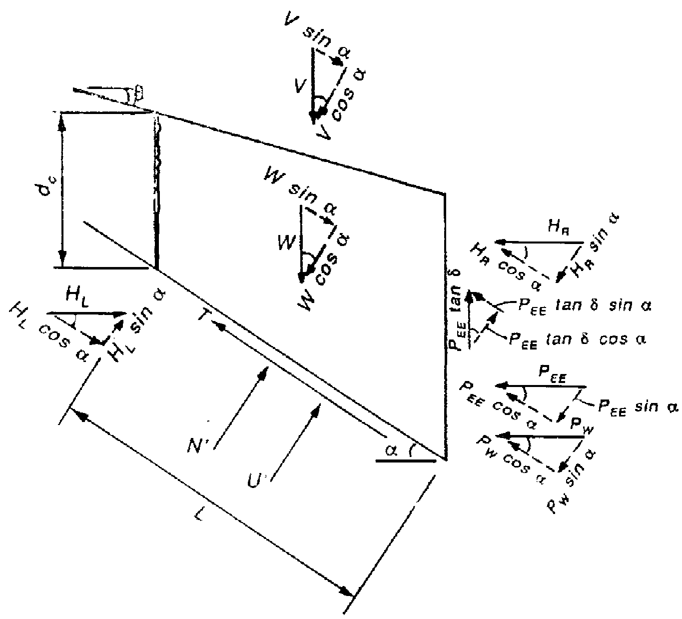
$p_{h2} = Kp_{v2} = 0.33927(2.9468) = 1.1766$ ksf

$p_{h3} = Kp_{v3} = 0.33927(3.8672) = 1.5441$ ksf



DERIVATION OF GENERAL WEDGE EQUATION FOR SINGLE WEDGE ANALYSIS
INCLUDING THE EFFECT OF WALL FRICTION (δ)

1. Effective Horizontal Earth Force. Given the following driving wedge which possesses both a c and a ϕ, an equation for P_{EE}, the horizontal effective earth force, will be derived.



Summing forces normal to the slip plane yields,

$$H_L \sin\alpha + U + N' - V\cos\alpha - H_R \sin\alpha + P_{EE}\tan\delta\cos\alpha - P_{EE}\sin\alpha - W\cos\alpha - P_w\sin\alpha = 0$$

Solving for N' yields,

$$N' = (H_R + P_{EE} + P_w - H_L)\sin\alpha + (V + W - P_{EE}\tan\delta)\cos\alpha - U = 0 \quad (1)$$

Summing forces tangent to the slip plane yields,

$$H_L \cos\alpha - T + V \sin\alpha + W \sin\alpha - H_R \cos\alpha - P_{EE} \tan\delta \sin\alpha - P_{EE} \cos\alpha - P_w \cos\alpha = 0$$

Solving for T yields,

$$T = (H_L - H_R - P_{EE} - P_w) \cos\alpha + (V + W - P_{EE} \tan\delta) \sin\alpha \tag{2}$$

According to the Mohr-Coulomb failure criterion,

$$T = N' \tan\phi + cL \tag{3}$$

Inserting Equations 1 and 2 into Equation 3 yields,

$$(H_L - H_R - P_{EE} - P_w) \cos\alpha + (V + W - P_{EE} \tan\delta) \sin\alpha$$

$$= [(H_R + P_{EE} + P_w - H_L) \sin\alpha + (V + W - P_{EE} \tan\delta) \cos\alpha - U] \tan\phi + cL$$

Simplifying and solving for P_{EE} yields,

$$P_{EE} = \frac{(W + V)(\sin\alpha - \cos\alpha \tan\phi) + (H_L - H_R - P_w)(\cos\alpha + \sin\alpha \tan\phi) + U \tan\phi - cL}{\sin\alpha \tan\phi + \sin\alpha \tan\delta + \cos\alpha - \cos\alpha \tan\delta \tan\phi}$$

$$P_{EE} = \frac{(W + V)(\tan\alpha - \tan\phi) + (H_L - H_R - P_w)(1 + \tan\alpha \tan\phi) + \dfrac{U \tan\phi}{\cos\alpha} - \dfrac{cL}{\cos\alpha}}{1 + \tan\alpha \tan\phi + \tan\delta (\tan\alpha - \tan\phi)} \tag{4}$$

The total effective earth force acts at an angle δ with respect to the horizontal. The total effective earth force is defined as

$$P = \frac{P_{EE}}{\cos\delta}$$

2. Soil Parameters. The horizontal effective earth force for a particular SMF can be calculated by inserting the factored soil parameters ϕ_d and c_d into Equation 5. This yields,

$$P_{EE} = \frac{(W + V)(\tan\alpha - \tan\phi_d) + (H_L - H_R - P_w)(1 + \tan\alpha \tan\phi_d) + \dfrac{U \tan\phi_d}{\cos\alpha} - \dfrac{c_d L}{\cos\alpha}}{1 + \tan\alpha \tan\phi_d + \tan\delta\,(\tan\alpha - \tan\phi_d)} \qquad (5)$$

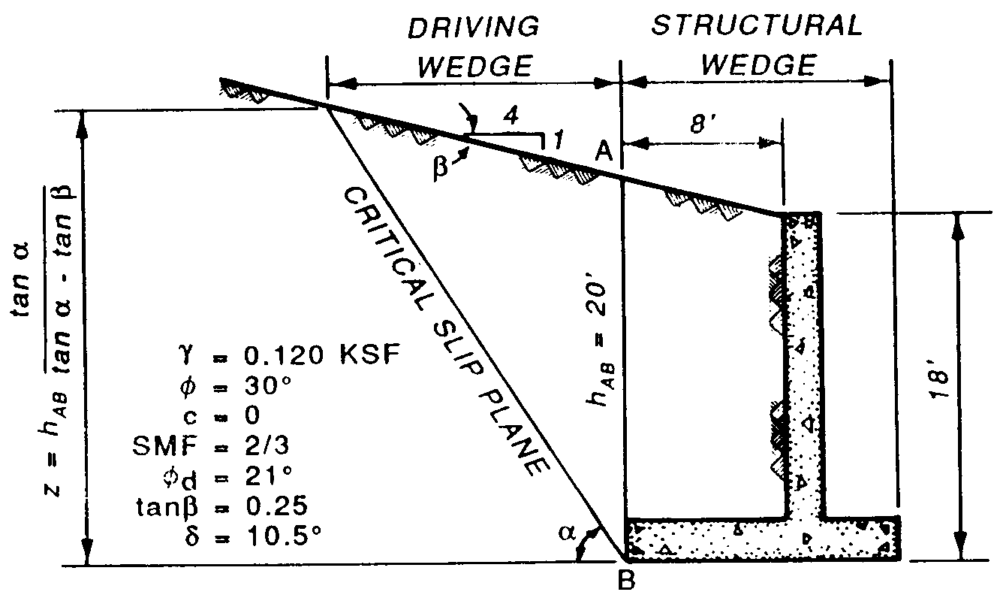
EXAMPLES OF EARTH PRESSURE COMPUTATIONS USING SIMPLIFIED PRESSURE COEFFICIENT METHOD INCLUDING THE EFFECTS OF WALL FRICTION

1. The following examples demonstrate the method of computing earth pressures using the simplified pressure coefficient method described in paragraph 5c of this ETL. The effect of wall friction is taken into account. The equations for the critical slip plane angle and the pressure coefficients are defined in paragraphs 6c and 6d.

2. Example 1 is taken from EM 1110-2-2502, Example 2, page M-5. Example 2 in this enclosure is the same as example 4 in Enclosure 2 with the addition of wall friction.

EXAMPLE 1

3. The earth pressures will be calculated for the soil geometry and properties given in the figure below. The earth pressure coefficients will be computed using pressure coefficients and compared against Coulomb's equation. The effects of wall friction will be taken into account in this example. Since the value of wall friction is affected by a number of factors, as described in paragraph 6a of this ETL, the value assigned to the wall friction was selected to demonstrate the mechanics of the procedure. Recommended values of wall friction will be addressed in subsequent engineering guidance.



4. Coulomb's equation (Equation 3-12 from EM 1110-2-2502) with θ = 90° reduces to

$$K_o = \frac{\cos^2 \phi_d \cos \delta}{\cos \delta \left[1 + \sqrt{\frac{\sin \phi_d \sin (\phi_d - \beta)}{\cos \delta \cos \beta}} \right]^2}$$

$$= \frac{\cos^2 21° \cos 10.5°}{\cos 10.5° \left[1 + \sqrt{\frac{\sin 21° \sin (21° - 14°)}{\cos 10.5° \cos 14°}} \right]^2}$$

$$= 0.05510$$

The horizontal effective earth force is computed as

$$P_{EE} = \frac{1}{2} K_o \gamma h^2 = \frac{1}{2} (0.5510)(0.12)(20)^2 = 13.224 \text{ kips/ft}$$

The vertical shear force is equal to

$$P_V = P_{EE} \tan \delta = 13.224 \tan 10.5° = 2.451 \text{ kips/ft}$$

5. The pressures and forces will now be computed using the simplified coefficient method. The critical slip plane angle is calculated using Equations 4 through 7 of this ETL as shown below.

$$A = \tan \phi_d + \tan \delta = \tan 21° + \tan 10.5° = 0.569203$$

$$c_1 = \frac{2 \tan \phi_d (\tan \phi_d + \tan \delta)}{A}$$

$$= \frac{2 \tan 21° (\tan 21° + \tan 10.5°)}{0.569203} = 0.767728$$

$$c_2 = \frac{\tan \phi_d [1 - \tan \phi_d (\tan ß + \tan \delta)] - \tan ß}{A}$$

$$= \frac{\tan 21° [1 - \tan 21° (\tan 14° + \tan 10.5°)] - \tan 14°}{0.569203}$$

$$= 0.122480$$

$$\alpha_{critical} = \tan^{-1} \left(\frac{C_1 + \sqrt{C_1 + 4C_2\ )}}{2} \right) = 42.092°$$

6. The pressure coefficients K and K_1 may now be calculated using Equations 9 and 10 of this ETL.

$$K = \frac{1 - \tan \phi_d \cot \alpha}{1 + \tan \phi_d \tan \alpha + \tan \delta (\tan \alpha - \tan \phi_d)}$$

$$= \frac{1 - \tan 21° \cot 42.092°}{1 + \tan 21° \tan 42.092° + \tan 10.5° (\tan 42.092° - \tan 21°)}$$

$$= 0.3985$$

$$K_1 = K \cdot \frac{\tan \alpha}{\tan \alpha - \tan \beta}$$

$$= \frac{0.3985 \tan 42.092°}{\tan 42.092° - \tan 14°}$$

$$= 0.5510$$

The horizontal effective earth force P_{EE} is calculated as

$$P_{EE} = \frac{1}{2} K_1 \gamma h^2 = \frac{1}{2} (0.5510)(0.12)(20)^2 = 13.224 \text{ kips/ft}$$

This agrees with the results obtained in paragraph 2.

7. The results will now be compared against the general wedge equation given in Equation 2 of this ETL.

$$W = \frac{\gamma h^2}{2(\tan \alpha - \tan \beta)} = \frac{0.12}{2(\tan 42.092° - \tan 14°)} = 36.7357 \text{ kips/ft}$$

$$P_{EE} = \frac{W(\tan \alpha - \tan \phi_d)}{1 + \tan \alpha \tan \phi_d + \tan \delta (\tan \alpha - \tan \phi_d)}$$

$$= \frac{36.7357(\tan 42.092° - \tan 21°)}{1 + \tan 42.092° \tan 21° + \tan 10.5° (\tan 42.092° - \tan 21°)}$$

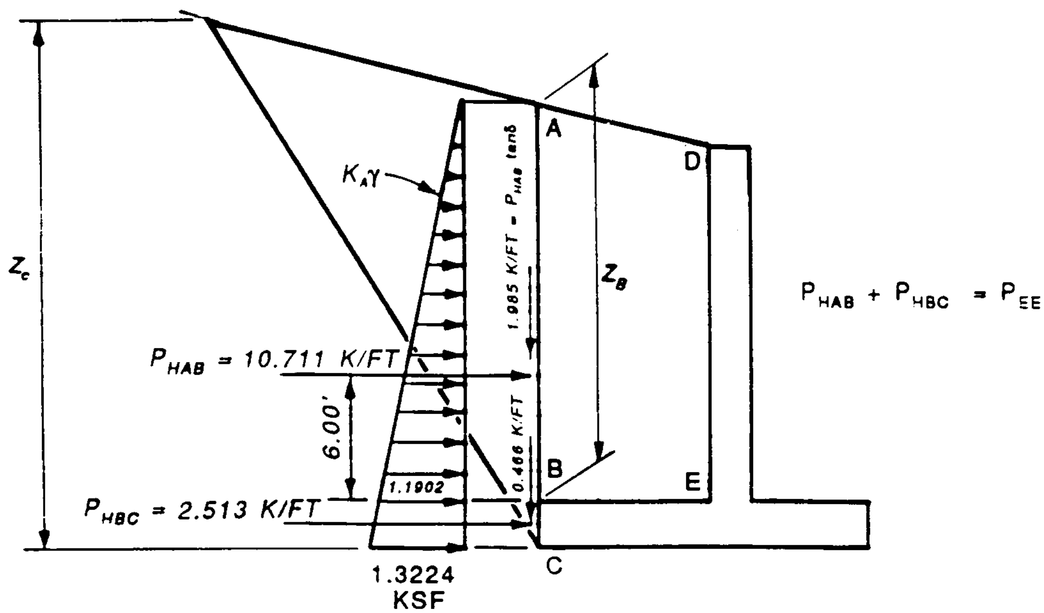
$$= 13.224 \text{ kips/ft}$$

This agrees with the previous solutions.

8. The lateral earth pressure distribution on the backfill may now be calculated. The pressures are calculated for two of the points shown on the following figure. The pressures can be calculated using the simplified method as follows:

$$p_{vc} = \gamma z_c = 0.12 (21.65) = 3.318 \text{ ksf}$$

$$p_{hc} = K p_{vc} = 0.3985 (3.318) = 1.322 \text{ ksf}$$

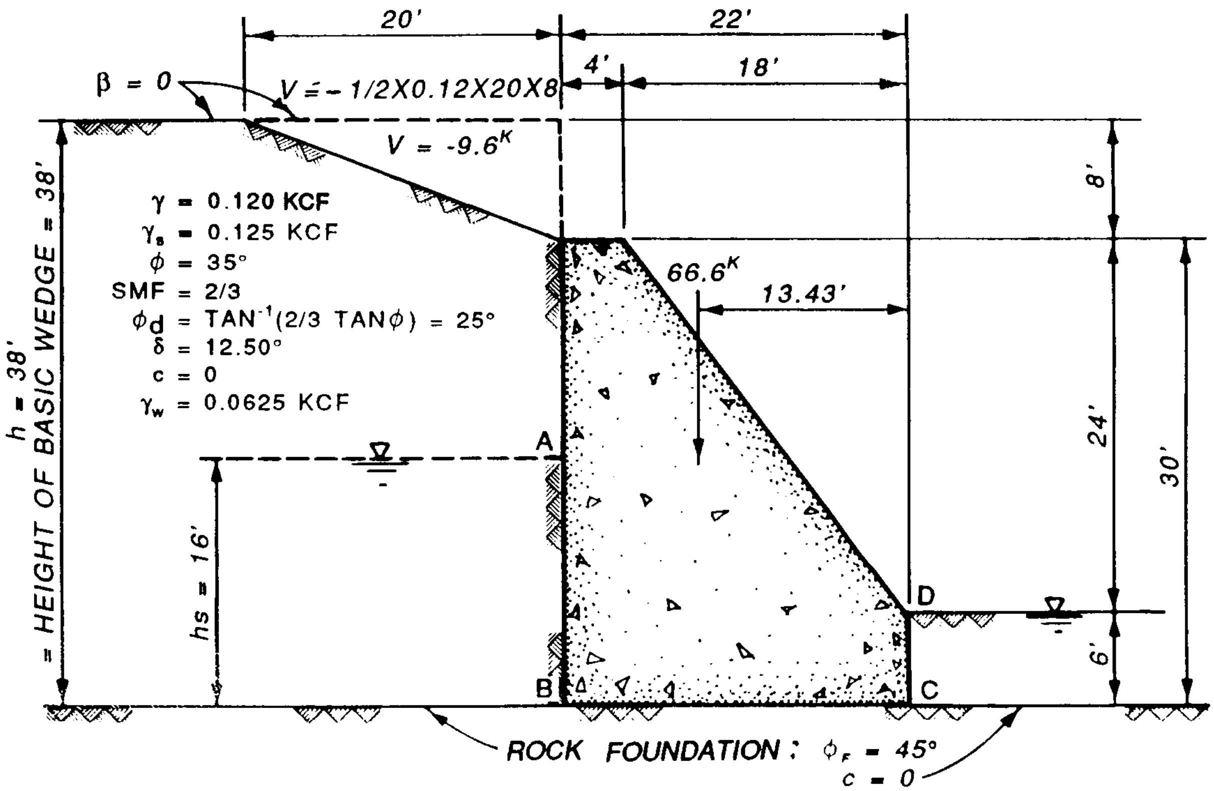


Since the pressure diagram is linear down to point C, the value for the pressure at point B may be calculated by proportions as follows:

$$p_{hB} = p_{hC} \frac{Z_B}{Z_C} = 1.322\ (18/20) = 1.190 \text{ ksf}$$

EXAMPLE 2

9. The earth pressures will be calculated for the soil geometry and properties given in the figure below. The earth pressures will be computed using the simplified coefficient method. The effects of wall friction will be taken into account in this example. Since the value of wall friction is affected by a number of factors, as described in paragraph 6a of this ETL, the value assigned to the wall friction was selected to demonstrate the mechanics of the procedure. Recommended values of wall friction will be addressed in subsequent engineering guidance.



10. The critical slip plane angle is calculated from Equations 4 through 7 of this ETL as shown below. Values for γ and V are taken from Example 4 in Enclosure 2.

$$A = \tan \phi_d + \tan \delta - \frac{2V(1 + \tan^2 \phi_d)}{\gamma h^2}$$

$$= \tan 25° + \tan 12.5° - \frac{2(-9.6)(1 + \tan^2 25°)}{0.1123(38)^2}$$

$$= 0.832149$$

$$c_1 = \frac{2 \tan \phi_d (\tan \phi_d + \tan \delta)}{A}$$

$$= \frac{2 \tan 25° (\tan 25° + \tan 12.5°)}{0.832149} = 0.771067$$

$$c_2 = \frac{\tan \phi_d (1 - \tan \phi_d \tan \delta)}{A}$$

$$= \frac{\tan 25° (1 - \tan 21° \tan 12.5°)}{0.832149}$$

$$= 0.502436$$

$$\alpha_{critical} = \tan^{-1}\left(\frac{C_1 + \sqrt{C_1 + 4C_2\ )}}{2}\right) = 50.016°$$

11. The pressure coefficient K may now be calculated using Equation 9 of this ETL.

$$K = \frac{1 - \tan \phi_d \cot \alpha}{1 + \tan \phi_d \tan \alpha + \tan \delta (\tan \alpha - \tan \phi_d)}$$

$$= \frac{1 - \tan 25° \cot 50.016°}{1 + \tan 25° \tan 50.016° + \tan 12.5° (\tan 50.016° - \tan 25°)}$$

$$= 0.35465$$

12. The lateral earth pressure distribution may now be calculated. The pressures are calculated for the points shown on the figure on the following page. The pressures are calculated as follows:

$p_{v1} = 0.12(21.067) = 2.5280$ ksf

$p_{v2} = 0.12(22) + 0.0767(1.849) = 2.7818$ ksf

$p_{v3} = 0.12(22) + 0.0767(16) = 3.8672$ ksf

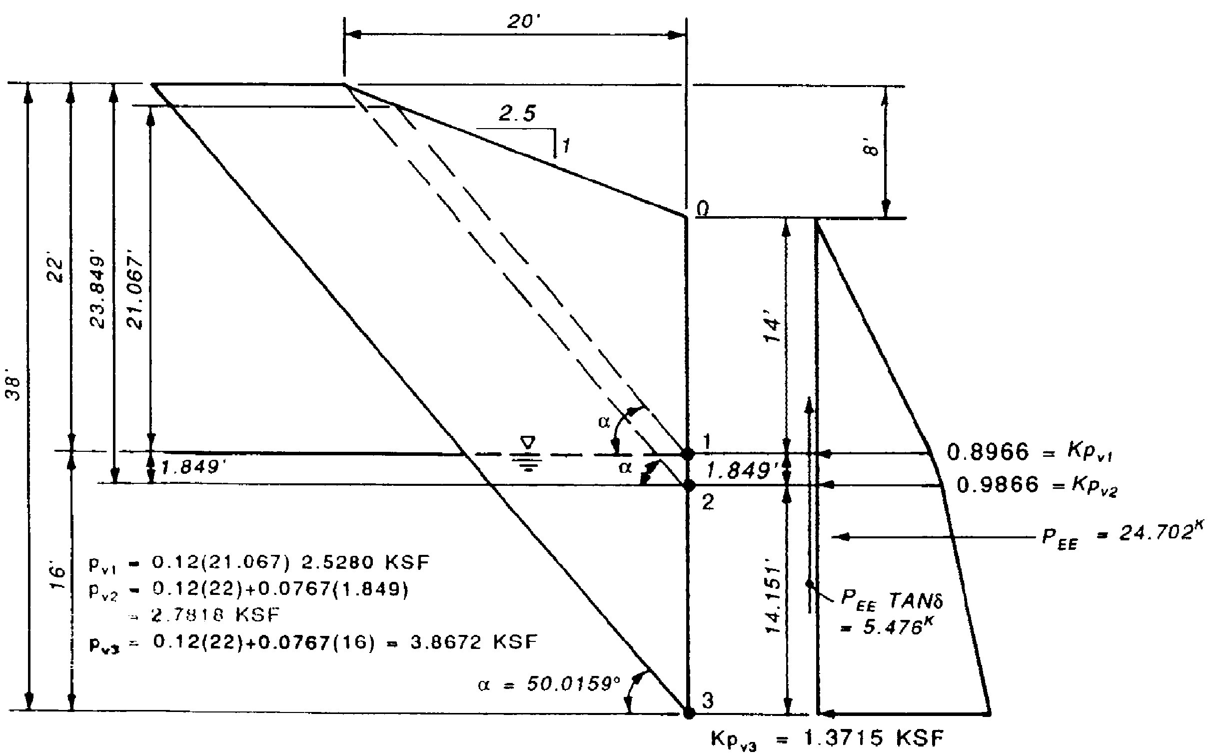
$p_{h1} = Kp_{v1} = 0.35465(2.5280) = 0.8966$ ksf

$p_{h2} = Kp_{v2} = 0.35465(2.7818) = 0.9866$ ksf

$p_{h3} = Kp_{v3} = 0.35465(3.8672) = 1.3715$ ksf

The vertical shear force is calculated as

$P_V = P_{EE} \tan \delta = 24.702 \tan 12.5° = 5.476$ kips



SMF VALUES WHEN THE RATIO $\tan ß/\tan \phi$ EXCEEDS 0.56

The following tables indicate the appropriate SMF value to use in Coulomb's equation (or the general wedge equation) to compute a K_o that is close to the value computed from the Danish Code Equation. The last two columns contain the recommended SMF and the corresponding K_o value calculated using Coulomb's equation. Note that a row of asterisks denotes the condition $ß > \phi_d$; Coulomb's equation is not valid for this condition.

PHI = 26.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
15.00	0.7070	0.4822	0.7086	0.7086	0.6667
16.00	0.7164	0.4920	0.7390	0.7164	0.6865
17.00	0.7258	0.5026	0.7818	0.7257	0.7070
18.00	0.7352	0.5143	0.8895	0.7351	0.7296
19.00	0.7445	0.5273	******	0.7444	0.7546
20.00	0.7537	0.5420	******	0.7536	0.7821
21.00	0.7629	0.5589	******	0.7628	0.8120
22.00	0.7720	0.5786	******	0.7719	0.8444
23.00	0.7811	0.6026	******	0.7810	0.8793
24.00	0.7901	0.6333	******	0.7900	0.9169
25.00	0.7990	0.6776	******	0.7994	0.9570

PHI = 27.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
15.00	0.6873	0.4608	0.6805	0.6805	0.6667
16.00	0.6965	0.4696	0.7059	0.6965	0.6756
17.00	0.7056	0.4792	0.7387	0.7056	0.6937
18.00	0.7147	0.4897	0.7874	0.7147	0.7139
19.00	0.7238	0.5012	******	0.7237	0.7362
20.00	0.7328	0.5141	******	0.7327	0.7608
21.00	0.7417	0.5286	******	0.7416	0.7876
22.00	0.7505	0.5453	******	0.7505	0.8168
23.00	0.7594	0.5649	******	0.7593	0.8484
24.00	0.7681	0.5887	******	0.7681	0.8825
25.00	0.7768	0.6193	******	0.7769	0.9190
26.00	0.7854	0.6635	******	0.7855	0.9582

PHI = 28.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
16.00	0.6768	0.4483	0.6764	0.6764	0.6667
17.00	0.6856	0.4570	0.7033	0.6856	0.6824
18.00	0.6945	0.4665	0.7389	0.6944	0.7004
19.00	0.7033	0.4768	0.7959	0.7032	0.7203
20.00	0.7120	0.4882	******	0.7119	0.7423
21.00	0.7207	0.5009	******	0.7206	0.7664
22.00	0.7293	0.5153	******	0.7293	0.7927
23.00	0.7378	0.5317	******	0.7378	0.8213
24.00	0.7463	0.5511	******	0.7462	0.8522
25.00	0.7547	0.5747	******	0.7547	0.8854
26.00	0.7631	0.6052	******	0.7632	0.9210
27.00	0.7714	0.6491	******	0.7718	0.9592

PHI = 29.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
17.00	0.6658	0.4359	0.6722	0.6722	0.6667
18.00	0.6744	0.4445	0.7008	0.6743	0.6888
19.00	0.6829	0.4538	0.7398	0.6828	0.7066
20.00	0.6914	0.4639	0.8095	0.6913	0.7263
21.00	0.6998	0.4751	******	0.6998	0.7480
22.00	0.7082	0.4877	******	0.7081	0.7717
23.00	0.7165	0.5018	******	0.7164	0.7975
24.00	0.7247	0.5181	******	0.7247	0.8254
25.00	0.7329	0.5373	******	0.7328	0.8556
26.00	0.7410	0.5607	******	0.7410	0.8880
27.00	0.7491	0.5909	******	0.7492	0.9228
28.00	0.7571	0.6346	******	0.7572	0.9601

PHI = 30.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
17.00	0.6462	0.4159	0.6440	0.6440	0.6667
18.00	0.6545	0.4236	0.6681	0.6544	0.6788
19.00	0.6628	0.4320	0.6985	0.6627	0.6947
20.00	0.6710	0.4411	0.7415	0.6710	0.7124
21.00	0.6792	0.4511	0.8394	0.6792	0.7319
22.00	0.6873	0.4621	******	0.6872	0.7532
23.00	0.6954	0.4745	******	0.6953	0.7765
24.00	0.7034	0.4884	******	0.7033	0.8018
25.00	0.7113	0.5045	******	0.7113	0.8291
26.00	0.7192	0.5235	******	0.7191	0.8587
27.00	0.7270	0.5466	******	0.7270	0.8904
28.00	0.7347	0.5765	******	0.7348	0.9245
29.00	0.7424	0.6200	******	0.7424	0.9610

PHI = 31.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
18.00	0.6348	0.4037	0.6386	0.6386	0.6667
19.00	0.6429	0.4113	0.6638	0.6428	0.6845
20.00	0.6508	0.4195	0.6964	0.6508	0.7004
21.00	0.6588	0.4285	0.7444	0.6587	0.7179
22.00	0.6666	0.4383	******	0.6666	0.7371
23.00	0.6745	0.4491	******	0.6744	0.7581
24.00	0.6822	0.4612	******	0.6821	0.7810
25.00	0.6899	0.4750	******	0.6898	0.8058
26.00	0.6976	0.4908	******	0.6976	0.8326
27.00	0.7051	0.5096	******	0.7051	0.8615
28.00	0.7126	0.5324	******	0.7126	0.8926
29.00	0.7201	0.5620	******	0.7202	0.9260
30.00	0.7274	0.6052	******	0.7276	0.9617

PHI = 32.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
19.00	0.6231	0.3917	0.6331	0.6331	0.6667
20.00	0.6309	0.3991	0.6595	0.6308	0.6899
21.00	0.6385	0.4071	0.6944	0.6385	0.7056
22.00	0.6462	0.4159	0.7488	0.6461	0.7229
23.00	0.6538	0.4255	******	0.6537	0.7419
24.00	0.6613	0.4361	******	0.6612	0.7626
25.00	0.6687	0.4481	******	0.6687	0.7851
26.00	0.6762	0.4616	******	0.6761	0.8094
27.00	0.6835	0.4772	******	0.6835	0.8357
28.00	0.6908	0.4956	******	0.6907	0.8641
29.00	0.6980	0.5182	******	0.6979	0.8946
30.00	0.7051	0.5475	******	0.7053	0.9273
31.00	0.7122	0.5902	******	0.7122	0.9624

PHI = 33.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
19.00	0.6036	0.3730	0.6051	0.6051	0.6667
20.00	0.6111	0.3797	0.6274	0.6110	0.6808
21.00	0.6185	0.3869	0.6552	0.6185	0.6949
22.00	0.6259	0.3948	0.6926	0.6259	0.7105
23.00	0.6333	0.4034	0.7558	0.6332	0.7276
24.00	0.6406	0.4128	******	0.6405	0.7463
25.00	0.6478	0.4232	******	0.6477	0.7667
26.00	0.6550	0.4349	******	0.6549	0.7888
27.00	0.6621	0.4482	******	0.6620	0.8128
28.00	0.6691	0.4635	******	0.6691	0.8386
29.00	0.6761	0.4817	******	0.6761	0.8665
30.00	0.6830	0.5039	******	0.6830	0.8964
31.00	0.6899	0.5329	******	0.6899	0.9286
32.00	0.6967	0.5751	******	0.6970	0.9630

PHI = 34.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
20.00	0.5916	0.3612	0.5984	0.5984	0.6667
21.00	0.5988	0.3678	0.6215	0.5987	0.6856
22.00	0.6059	0.3748	0.6507	0.6058	0.6997
23.00	0.6130	0.3825	0.6911	0.6130	0.7151
24.00	0.6201	0.3909	0.7679	0.6201	0.7320
25.00	0.6271	0.4001	******	0.6271	0.7504
26.00	0.6340	0.4103	******	0.6340	0.7705
27.00	0.6409	0.4218	******	0.6409	0.7923
28.00	0.6478	0.4348	******	0.6478	0.8158
29.00	0.6545	0.4499	******	0.6545	0.8413
30.00	0.6612	0.4677	******	0.6612	0.8686
31.00	0.6678	0.4896	******	0.6678	0.8981
32.00	0.6744	0.5182	******	0.6745	0.9297
33.00	0.6809	0.5600	******	0.6814	0.9636

PHI = 35.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
21.00	0.5792	0.3495	0.5914	0.5914	0.6667
22.00	0.5862	0.3559	0.6154	0.5861	0.6901
23.00	0.5930	0.3628	0.6460	0.5930	0.7040
24.00	0.5999	0.3703	0.6899	0.5998	0.7193
25.00	0.6066	0.3785	0.7989	0.6066	0.7360
26.00	0.6134	0.3875	******	0.6133	0.7542
27.00	0.6200	0.3975	******	0.6200	0.7740
28.00	0.6266	0.4087	******	0.6266	0.7955
29.00	0.6332	0.4214	******	0.6331	0.8187
30.00	0.6396	0.4362	******	0.6396	0.8437
31.00	0.6460	0.4538	******	0.6461	0.8706
32.00	0.6524	0.4753	******	0.6523	0.8996
33.00	0.6587	0.5034	******	0.6588	0.9307
34.00	0.6649	0.5447	******	0.6654	0.9641

PHI = 36.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
22.00	0.5666	0.3380	0.5842	0.5842	0.6667
23.00	0.5733	0.3442	0.6090	0.5732	0.6942
24.00	0.5799	0.3509	0.6412	0.5798	0.7081
25.00	0.5864	0.3582	0.6891	0.5864	0.7232
26.00	0.5929	0.3662	******	0.5928	0.7398
27.00	0.5994	0.3749	******	0.5993	0.7577
28.00	0.6057	0.3847	******	0.6057	0.7773
29.00	0.6121	0.3956	******	0.6120	0.7984
30.00	0.6183	0.4081	******	0.6183	0.8212
31.00	0.6245	0.4226	******	0.6245	0.8458
32.00	0.6307	0.4398	******	0.6306	0.8724
33.00	0.6367	0.4610	******	0.6366	0.9009
34.00	0.6427	0.4887	******	0.6428	0.9316
35.00	0.6487	0.5294	******	0.6491	0.9645

PHI = 37.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
22.00	0.5473	0.3209	0.5558	0.5558	0.6667
23.00	0.5538	0.3265	0.5766	0.5537	0.6857
24.00	0.5601	0.3325	0.6023	0.5601	0.6981
25.00	0.5665	0.3391	0.6362	0.5664	0.7119
26.00	0.5727	0.3461	0.6889	0.5727	0.7269
27.00	0.5790	0.3539	******	0.5789	0.7432
28.00	0.5851	0.3625	******	0.5850	0.7610
29.00	0.5912	0.3720	******	0.5911	0.7802
30.00	0.5973	0.3827	******	0.5973	0.8010
31.00	0.6033	0.3949	******	0.6033	0.8235
32.00	0.6092	0.4091	******	0.6091	0.8478
33.00	0.6151	0.4259	******	0.6150	0.8740
34.00	0.6208	0.4467	******	0.6208	0.9021
35.00	0.6266	0.4739	******	0.6267	0.9324
36.00	0.6322	0.5140	******	0.6327	0.9649

PHI = 38.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
23.00	0.5345	0.3097	0.5474	0.5474	0.6667
24.00	0.5407	0.3151	0.5687	0.5406	0.6894
25.00	0.5468	0.3210	0.5953	0.5467	0.7018
26.00	0.5528	0.3273	0.6310	0.5528	0.7154
27.00	0.5588	0.3342	0.6894	0.5588	0.7302
28.00	0.5648	0.3417	******	0.5647	0.7464
29.00	0.5707	0.3501	******	0.5707	0.7639
30.00	0.5765	0.3593	******	0.5765	0.7829
31.00	0.5823	0.3698	******	0.5822	0.8035
32.00	0.5880	0.3817	******	0.5880	0.8256
33.00	0.5937	0.3956	******	0.5937	0.8496
34.00	0.5993	0.4120	******	0.5993	0.8754
35.00	0.6048	0.4324	******	0.6048	0.9032
36.00	0.6102	0.4591	******	0.6104	0.9331
37.00	0.6156	0.4986	******	0.6160	0.9653

PHI = 39.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
24.00	0.5214	0.2986	0.5387	0.5387	0.6667
25.00	0.5273	0.3038	0.5605	0.5273	0.6928
26.00	0.5332	0.3095	0.5879	0.5331	0.7052
27.00	0.5390	0.3157	0.6255	0.5389	0.7186
28.00	0.5447	0.3224	0.6913	0.5447	0.7333
29.00	0.5504	0.3297	******	0.5503	0.7493
30.00	0.5560	0.3378	******	0.5560	0.7666
31.00	0.5616	0.3468	******	0.5616	0.7853
32.00	0.5671	0.3570	******	0.5671	0.8056
33.00	0.5726	0.3686	******	0.5726	0.8275
34.00	0.5780	0.3821	******	0.5779	0.8512
35.00	0.5833	0.3982	******	0.5832	0.8767
36.00	0.5886	0.4182	******	0.5886	0.9041
37.00	0.5938	0.4444	******	0.5937	0.9337
38.00	0.5989	0.4831	******	0.5993	0.9656

PHI = 40.00°

ß (Deg)	$K_{oß}$ (Danish)	K_o (SMF=1)	K_o (SMF=2/3)	Recommended K_o	Recommended SMF
25.00	0.5082	0.2876	0.5297	0.5297	0.6667
26.00	0.5138	0.2927	0.5519	0.5137	0.6960
27.00	0.5194	0.2982	0.5802	0.5193	0.7082
28.00	0.5249	0.3041	0.6197	0.5249	0.7216
29.00	0.5304	0.3106	0.6954	0.5303	0.7361
30.00	0.5358	0.3177	******	0.5357	0.7519
31.00	0.5412	0.3256	******	0.5411	0.7690
32.00	0.5465	0.3344	******	0.5464	0.7876
33.00	0.5518	0.3442	******	0.5518	0.8076
34.00	0.5570	0.3556	******	0.5569	0.8292
35.00	0.5621	0.3687	******	0.5621	0.8526
36.00	0.5672	0.3845	******	0.5672	0.8778
37.00	0.5722	0.4040	******	0.5723	0.9049
38.00	0.5771	0.4296	******	0.5773	0.9342
39.00	0.5820	0.4677	******	0.5825	0.9658

EXAMPLE OF LIMITATION OF 2/3 SMF

1. The following example will demonstrate that if ß is large compared to ϕ (the ratio tan ß/tan ϕ > 0.56), the value of the horizontal earth pressure coefficient computed from Coulomb's equation using an SMF of 2/3 will exceed the value of the horizontal pressure coefficient computed from the Danish Code equation. In some cases, this increase will be overly conservative.

2. For a smooth (no wall friction), vertical wall with a soil having ϕ = 30° and ß = 21°, the horizontal earth pressure coefficients will be computed by the Danish Code equation and Coulomb's equation.

Danish Code Equation (Equation 3-5, EM 1110-2-2502)

$$K_o = (1 - \sin \phi)(1 + \sin \beta)$$

$$= (1 - \sin 30°)(1 + \sin 21°)$$

$$= 0.6792$$

Coulomb's Equation with SMF = 2/3 (Equation 3-14, EM 1110-2-2502)

$$\phi_d = \tan^{-1} (SMF \tan \phi)$$

$$= \tan^{-1} (2/3 \tan 30°)$$

$$= 21.0517°$$

$$K_o = \frac{\cos^2 \phi_d}{\left[1 + \sqrt{\frac{\sin \phi_d \sin (\phi_d - \beta)}{\cos \delta \cos \beta}}\right]^2}$$

$$= \frac{\cos^2 21.057°}{\left[1 + \sqrt{\frac{\sin 21.0517° \sin (21.0517° - 21°)}{\cos 21°}}\right]^2}$$

$$= 0.8394$$

Coulomb’s Equation with SMF = 0.7319 (from Table in Enclosure 5 for ϕ = 30°)

$$\phi_d = \tan^{-1} (\text{SMF} \tan \phi)$$

$$= \tan^{-1} (0.7319 \tan 30°)$$

$$= 22.9071$$

$$K_o = \frac{\cos^2 22.9071°}{\left[1 + \sqrt{\dfrac{\sin 21.0517° \sin (22.9071° - 21°)}{\cos 21°}}\right]^2}$$

$$= 0.6791$$

3. From the summary of the results below, Coulomb’s equation with an SMF of 2/3 results in an at-rest earth pressure coefficient which exceeds the Danish Code equation.

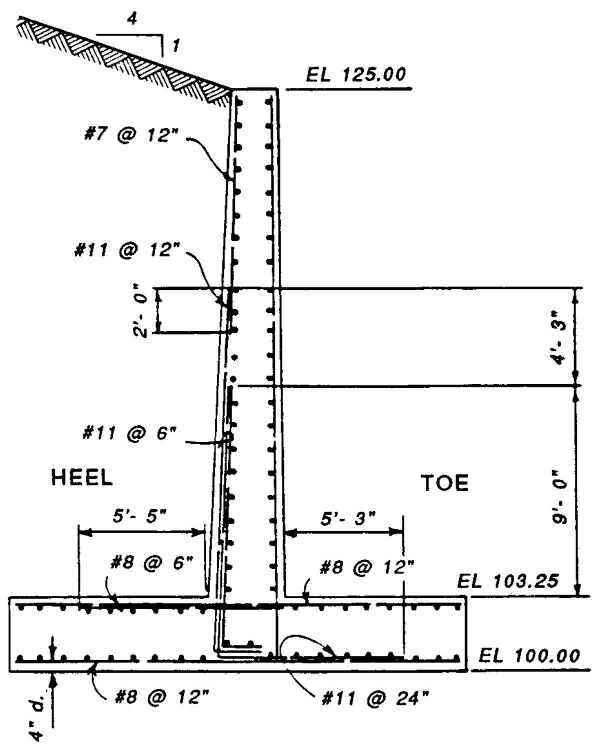
At-rest, Danish Code equation: $K_o = 0.6792$

Coulomb’s equation with SMF = 2/3: $K_o = 0.8394$

Coulomb’s equation with SMF = 0.7319: $K_o = 0.6791$

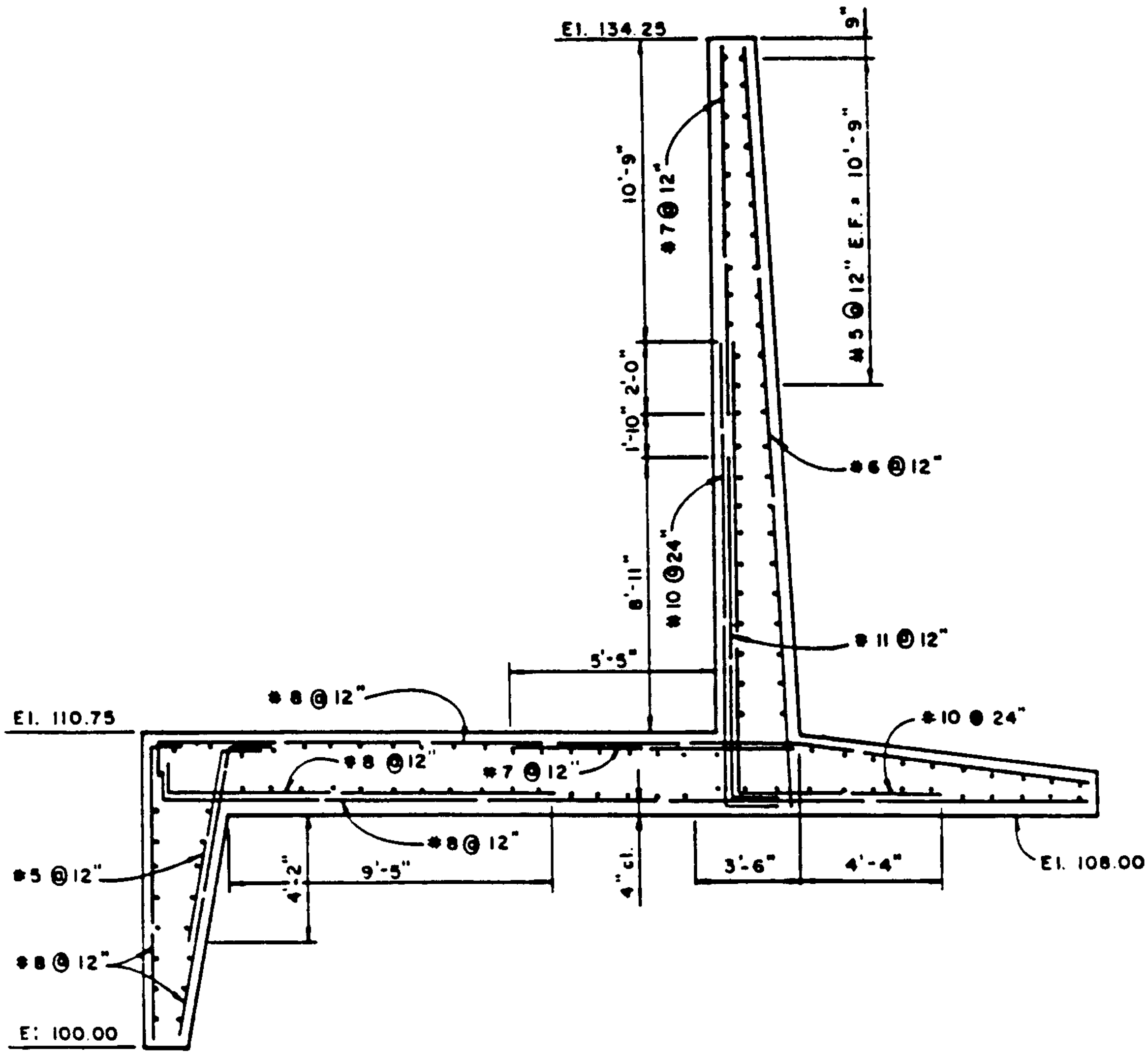
TYPICAL STEEL DETAILS

1. A typical reinforcement for a cantilever retaining wall is shown below.



NOTES: 1. ALL REINF. TO BE #6 @ 12", EXCEPT AS SHOWN.
2. ALL HOOKS SHOWN ARE ACI STANDARD HOOKS.
3. MINIMUM CLEAR CONCRETE COVER TO BE 3" EXCEPT AS SHOWN.

2. A typical reinforcement for a floodwall is shown below.



NOTES:

1. All longitudinal reinforcement to be #6 @ 12" E.F. except as noted.
2. Concrete cover for reinforcement to be 3 inches except as noted.
3. All hooks shown to be ACI standard hooks.